THEORETICAL UNCERTAINTY OF ORIFICE FLOW MEASUREMENT

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INTRODUCTION

Orifice meters are the most common meters used for fluid flow measurement, especially for measuring hydrocarbons. Meters are rugged, mechanically simple, and well suited for field use under extreme weather conditions. In 1779, an Italian physicist named Giovanni B. Venturi (1746-1822) performed the first recorded work that used orifices for the measurement of fluid flow. Many years of field experience with wide range of meter sizes, variety of fluids, and numerous investigative tests have identified all major contributing factors of measurement uncertainty of orifice flowmeters. Because of their long history of use and dominance in the fluid flow measurement, their designs, installation requirements, and equations for flow rate calculation have been standardized by different organizations in the United States and internationally [Ref 1-7]. These standards provide the guideline for the users to achieve accurate flow measurement and minimize measurement uncertainty. This paper discusses different factors that contribute to the measurement inaccuracy and provide an awareness to minimize or eliminate these errors.

Many factors which influence the overall measurement uncertainty are associated with the orifice meter application. Major contributors to measurement uncertainty include the predictability of flow profile, fluid properties at flowing condition, precision of empirical equation for discharge coefficient, manufacturing tolerances in meter components, and the uncertainty associated with secondary devices monitoring the static line pressure, differential pressure across the orifice plate, flowing temperature, etc. An orifice flowmeter is a very forgiving device and for most applications, with normal care in installation and instrumentation, the measurement accuracy is consistently better than ±1%. If the measurement error is greater than ±1%, one must look for obvious errors in installation and instruments. Major factors contributing to the measurement uncertainty for a thin, concentric, square-edged orifice flowmeter are as follows:

(a) Tolerances in prediction of coefficient of discharge,
(b) Predictability in defining the physical properties of the flowing fluid,
(c) Fluid flow condition,
(d) Construction tolerances in meter components,
(e) Uncertainty of secondary devices/instrumentation, and
(f) Data reduction and computation.

Different factors under each of the above areas are discussed with precautionary measures and installation procedures to minimize or eliminate measurement uncertainty.

COEFFICIENT OF DISCHARGE

Derivation of the basic flow equation for an orifice flowmeter is based on physical laws. Any derivation is accurate when all assumptions used to develop the equation are valid. The basic equation, based on simplified flow and fluid properties, is modified to an empirical form to adjust for complex multidimensional viscous fluid-dynamic effects. In addition, for compressible fluids, an empirical expansion factor is applied to the discharge coefficient equation to adjust for the fluid density variation due to changes in pressure upstream and downstream of the orifice plate. A number of discharge coefficient equations are used in different standards. The latest discharge coefficient equation is the API 14.3 - Part I (AGA-3) - 1990 [Ref. 1]. This empirical equation was developed from a large data base with better controlled and quantified independent variables. Although it does not mean that other data bases or equations are of inferior quality but it is known that insufficient information exists for different independent variables of those data bases [Ref. 3-5].

The orifice plate discharge coefficient (C_d) is the ratio of the true flow to the theoretical flow and is applied to the theoretical flow equation to obtain the actual (true) flow. An important nondimensional flow parameter is the Reynolds number, the ratio of the inertial force to the viscous force for a flowing fluid. The pipe Reynolds number is used to correlate the variations in the orifice plate coefficient of discharge (C_d) with changes in fluid's properties, flow rate, and orifice meter geometry. There is a limit to the value of Reynolds number (4000) below which the standard empirical equations of discharge coefficients are not valid to the same tolerance. For the normal operating flow range of gases, the pipe Reynolds numbers are orders of magnitude higher than this low limit of 4,000. For viscous oil, specially with low specific gravity, the lower limit of Reynolds number may be important.

The coefficient of discharge is a function of the Reynolds number while the Reynolds number is a function of flow rate which is computed using the coefficient of discharge value.

The bad news is that the determination of the actual flow rate is an iterative process of calculating Reynolds number and corresponding discharge coefficient but the good news is that for practical applications the value of the discharge coefficient converges to a final value after the first or the second iteration. For field measurement performed by a micro-processor based system, the iterative solution can easily be achieved during data acquisition process. Using the averaged differential pressure from the chart and a fixed discharge coefficient value, it may not be possible to account for the effect of varying discharge coefficient value at different flow rates. Therefore, averaged differential pressure data obtained from a chart could introduce certain measurement errors. For the Reynolds number values at the maximum and minimum differential pressure on the chart, the maximum possible measurement uncertainty can be established. Again, the good news is that for most hydrocarbon flow under normal operating conditions, this error is negligible.

PHYSICAL PROPERTIES OF FLOWING FLUID

All empirical equations and standards for concentric, square-edged orifice meters apply to steady state flow conditions for fluids that, for all practical purposes, are considered to be clean, single phase, homogeneous, and Newtonian. In the petroleum, petrochemical, and natural gas industries, all gases, most liquids, and most of the dense phase fluids usually are considered Newtonian fluids.

In practice, some fluid's flow rates are expressed in volume units at base (standard or reference) conditions. The base conditions can differ between countries, states and even between industries. Volumetric flow rate is measured at the operating flowing conditions and then converted to standard volume with respect to the base conditions. Therefore, the base conditions must be identified when the flow rate is expressed in standard volumetric measure. Conversion of the volume flow rate to the mass rate of flow is through the density of the flowing fluids. Again the measured differential pressure used to determine the volumetric flow rate is dependent on the fluid density. The accuracy in predicting the flow density is important for the precision of flow rate measurement. In practice, the fluid properties are defined as a function of the operating pressure and temperature monitored by the secondary devices. When measuring low velocity fluids, whose density is sensitive to temperature changes, the flow tube should be thermally insulated between the primary element and the temperature device because significant temperature variation between the thermal well and the orifice taps will affect the measurement.

The absolute viscosity of the fluid at flowing conditions is required to compute the Reynolds number. For high Reynolds number the effect of viscosity is negligible and the viscosity variation is ignored but for low Reynolds number applications, e.g., viscous oil flow, an inaccurate viscosity value may have a significant effect on the flow computation.

The isentropic exponent, k, important for compressible fluids, is a function of temperature and for some fluid is function of pressure also. From a practical standpoint and for normal operating conditions the flow equation is essentially insensitive to the small variations in the isentropic exponent.

FLUID FLOW CONDITION

The data base for an empirical equation for coefficient of discharge is for steady state fully developed pipe flow profile with negligible or no swirl flow and flow fluctuations. The flow profile of a fully developed pipe flow does not change from one flow cross-sectional area to another downstream location. Profile deviations from the ideal fully developed flow profile introduce flow measurement uncertainty. Profile distortions, swirl flow and flow fluctuations at the orifice are introduced by piping installation upstream of the flowmeter. In-situ test results are available in the literature [Ref. 8,9].

The validity of empirical coefficient of discharge is for flows that are subsonic through the orifice and the meter and for fluid that does not undergo any change of phase as it passes through the orifice. There is also an allowable limit to the deviation of the actual flow profile from the fully developed flow profile. The empirical coefficient calculated from the equations are valid only if the dynamic similarity exists between the metering installation and the experimental data base and the physics of fluid does not change. This dynamic similarity applies to the flow and the geometric similarity of the flowmeter. The similarity of flow profile and flow pattern are achieved through the use of flow conditioner and a minimum upstream and downstream straight pipe lengths for the orifice flowmeter. In the data base used to determine the empirical equation of the discharge coefficient, undisturbed flow conditions or near fully-developed flow profile were achieved by using flow conditioners and straight lengths of meter tube both upstream and downstream of the orifice plate.

In both the API/GPA and European Community (EC) experiments (part of the data base), the undisturbed flow condition was defined as the equivalent of a symmetrical, swirl-free velocity profile in circular pipes, located approximately 45 pipe diameters downstream of a Sprenkle flow conditioner and with an average internal surface wall roughness, R_a, of approximately 150 micro inches. In many applications these dimensional requirements are not achievable yet the empirical equation values are used to calculate the flow rate. The error introduced by nonconforming flow profile is not predictable and will contribute to the measurement uncertainty. For nonconforming flow profile application, in-situ calibration is advised if possible and feasible.

An appreciable pulsation in flow at the orifice flowmeter will generate measurement error because the flow fluctuation will affect the differential pressure reading.
The flow induced fluctuating differential pressure reading is a nonlinear function of the flow rate, therefore, the flow rate computed by using a time averaged differential pressure will introduce measurement uncertainty. To obtain precise measurement, the flow pulsation must be suppressed.

There are considerable study and experimentation to evaluate the requirements and methods necessary to achieve pulsation reduction. There are instruments that indicate the presence of pulsation and determine the effectiveness of pulsation suppression practices. To date, no theoretical or empirical adjustment for orifice flow measurement exists for pulsating flow application.

Disturbances in the flow profile increase the measurement uncertainty. For precise measurement, all flow disturbance should be minimized or eliminated by following installation requirements of the standard. The orifice flowmeter with diameter ratio of 0.6 or less has negligible effect of profile distortion on the discharge coefficient, therefore, using beta plates of 0.6 or less should reduce measurement uncertainty where less than ideal flow profile is expected.

CONSTRUCTION TOLERANCES IN METER COMPONENTS

The new API 14.3 - Part II (AGA-3) - 1991 Standard [Ref. 2] has significant changes to the mechanical tolerance requirements for the orifice meter components. Since the standard encompasses a wide range of diameter ratios for which experimental results are available, some of the tolerances are significantly more stringent than the tolerances in the previous standards.

Orifice Plate: The applicable diameter ratio range by the standard is between 0.10 and 0.75 but minimum uncertainty of the orifice coefficient of discharge may be achieved with diameter ratios between 0.2 and 0.6 and orifice bore diameters greater than or equal to 0.45 inches.

The orifice bore diameter used in the calculation of flow is a function of the plate temperature and the thermal expansion property of the plate material. Therefore, the bore diameter measured for the plate temperature at the time of measurement should be adjusted to the reference temperature of 68°F. The effect of the thermal expansion can be significant when the meter tube and the plates have different thermal expansion coefficients and the operating temperatures are an order of magnitude different from the reference temperature for the plate. This measurement error can be corrected if the plate dimension at a reference temperature is known.

The tolerance of the smoothness and flatness of the plate under static conditions are the limits of the data base. The effect of these parameters on the empirical coefficient of discharge is not known when these tolerance limits are exceeded. The same criterion is applied to the limits of other mechanical tolerances like edge sharpness, roundness of the bore, thickness of the plate, bevel angle, etc. Major manufacturers of orifice plates conform to these limits. If there is any doubt about any of the mechanical tolerance of the plate for accurate metering, the orifice plate should be replaced.

Orifice Plate Gasket or Sealing Device Recesses and Protrusions: The sealing device tolerances and restriction apply to location immediately upstream and downstream of the face of the orifice plate (Figure 1).

(a) Protrusion of the sealing device or gasket into the pipe bore is not permitted.

(b) The depth of recess is unrestricted provided the gap between the plate and the pipe is 0.25 inches or less.

(c) For recesses of 0.25 inches but less than 0.5 inches with depth of the recess less than or equal to 0.25% of the pipe diameter does not have any diametric ratio limitation or additional measurement uncertainty.

For all other recesses larger widths or greater depth generate additional uncertainty. Detailed results of the study are presented in Ref. 10.

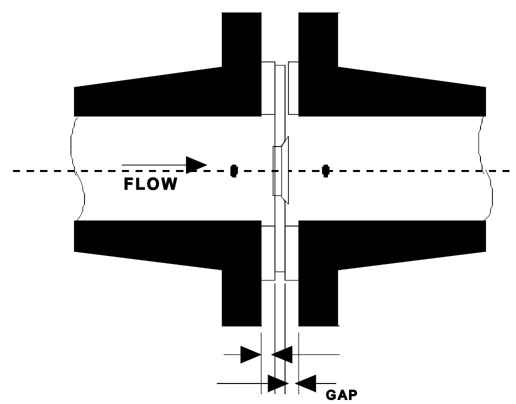

FIGURE 1: RECESSES & PROTRUSIONS

Orifice Fittings: A class of orifice plate holders, widely used in industry, provide ease of plate change and is the orifice fitting. With these devices, it is possible, to reproduce orifice coefficient within the uncertainty limits as would be found for an orifice plate held between flanges. In order to accomplish that goal, the orifice fitting must satisfy all the manufacturing tolerances stated in the Standards. Some critical inspection that are unique to these fittings should be performed. All specified tolerances should be carefully evaluated because total machining tolerances of all the mating parts can add up to exceed allowable limits.

The concentricity requirements of the upstream and downstream pipe to the orifice fitting and to each other reduces the measurement uncertainty. The roundness and surface condition of the pipe at the weld and at least two diameter upstream from the face of the plate must conform with all the specified tolerances.

A positive seal of the orifice plate in an orifice fitting must be verified. Any leakage of fluid between the seal and the seat may introduce error and loss of revenue for custody transfer.

The location of the pressure taps from the face of the plate is critical and deviations beyond the allowable limits will introduce additional uncertainty. Orifice fittings must conform to the allowable tolerance to maintain the measurement accuracy. Experimental results are presented in Ref. 11.

Other components like pressure tap diameter, edges of the tap, flow conditioners, etc., have mechanical tolerances but proper inspection and quality control should eliminate the associated errors.

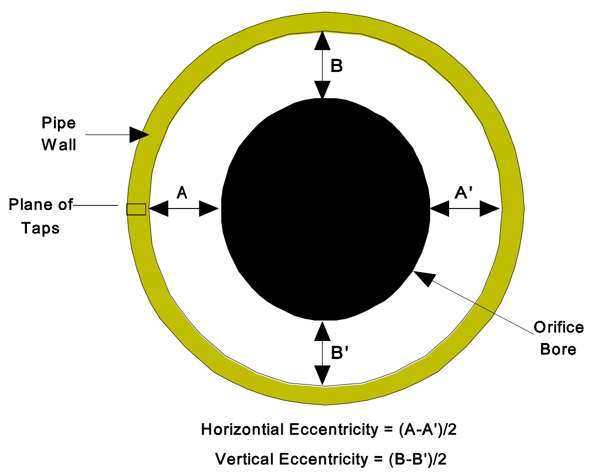

FIGURE 2: ECCENTRICITY MEASUREMENT

Plate Eccentricity: Concentricity of the orifice bore to the pipe is critical for measurement accuracy. The plate eccentricity is defined as shown in Figure 2. Details of errors due to eccentricity of the plate are presented in Ref. 12. Eccentricity of the plate in any direction from the tap results in measurement error but within the allowable limits the error is negligible. Measurement error for eccentricity toward the tap is more than the error introduced by same eccentricity in any other direction. There are maximum allowable tolerance as a function of diameter ratio and line size. When the eccentricity with respect to the tap is known for a meter tube, the measurement error can be predicted for certain line sizes. The allowable orifice plate bore eccentricity, measured parallel to the axis of the pressure tap, for which measurement error is negligible, is given by

$$\epsilon \leq \frac{0.0025 \cdot D}{0.1 + 2.3 \cdot \beta^4}$$

where, ε is the orifice plate bore eccentricity. This dimensional limit is critical for any orifice flowmeter.

The allowable eccentricity limit can be relaxed when two diametrically opposite taps are tied together and the differential pressure is the mechanically averaged value. With two taps tied together the allowable limit can be doubled. Note that the diameter ratio is in the denominator so the decreasing beta ratio increases the allowable eccentricity for the same line size.

The orifice plate holder should maintain the plane of the orifice plate at an angle of 90° to the meter tube axis.

Meter Tube: The straight pipe of same diameter, upstream and downstream of the orifice plate, including the straightening vanes, and the plate holder, if used, is the meter tube. There are limits to the roughness and roundness of the pipe. In general these limits are imposed because the meter tubes used to generate the data base was within those limits and the empirical coefficient of discharge may not be valid when these limits are exceeded.

To assure accurate flow measurement, the fluid should enter the orifice plate with a fully developed flow profile, free from swirl or vortices. Some common piping installations have been studied with regard to their effect on metering accuracy and all orifice meter standards recommend minimum upstream and downstream lengths of meter tube with and without flow conditioners to achieve desired undisturbed flow condition at the orifice plate.

The roundness of the meter tube upstream and downstream of the plate is important. Within one diameter upstream of the plate any measured meter tube diameter cannot exceed the limits of ±0.25% of the mean tube diameter. For the downstream the tolerance is more relaxed where any measured meter tube diameter cannot exceed the limit of ±0.5% of the mean diameter.

Abrupt changes of the inside meter tube surface due to shoulders offsets, ridges, welding, seams, etc., is to be avoided with exceptions of the recesses on either side of the plate allowed within the limits specified by the Standards.

SECONDARY DEVICES

The secondary devices are the instruments used to monitor the flowing fluid temperature, pressure, and the differential pressure across the orifice plate. For normal applications, the line pressure and temperature measurement errors have negligible effect on the flow measurement but differential pressure devices have a significant influence. Parameters affecting the accuracy of the differential pressure monitoring device include ambient temperature, static pressure, hysteresis, linearity, repeatability, long term stability and drift, and uncertainty of the calibration standard. The stated accuracy of most differential pressure measuring devices is expressed in percentage of the full scale reading. So the error band of the differential pressure in percentage of the actual reading increases with decreasing differential pressures.

For some applications, parallel orifice meters are installed to meet the uncertainty and rangeability requirements of the user. A stacked differential pressure devices calibrated over different ranges is often installed to minimize uncertainty while increasing rangeability for a given orifice plate.

DATA REDUCTION AND COMPUTATION

Error in flow rate computation depends on the accuracy of defining physical properties of the flowing fluid which is often computed by the microprocessor based flow computers. Computation of the physical properties, especially for gas flows, is dependent on the constituents of gas in the flowing fluid. All fixed input and critical parameters affecting the flow rate computation should be verified to reduce bias error in flow measurement.

UNCERTAINTY DETERMINATION

All major factors affecting the measurement accuracy are discussed in the preceding sections with possible remedial steps to minimize the measurement uncertainty. When the precision of measuring devices for each parameter, e.g., diameter, differential pressure, temperature, etc., is known, the flow rate measurement uncertainty associated with each parameter can be predicted. This prediction method is based on the theoretical relationship of each parameter to the flow rate.

A number of standards are available to evaluate and estimate contribution to uncertainty by each measured parameter [Ref. 6,7]. Each term in the flow measurement equation and its exponent defines the magnitude of uncertainty. The method of estimation is defined mathematically and is based on statistical analysis and theories. Without going to the theoretical details the effect of the diameter ratio on the empirical discharge coefficient at infinite Reynolds number is shown in Figure 3. Similar prediction is possible for many other parameters.

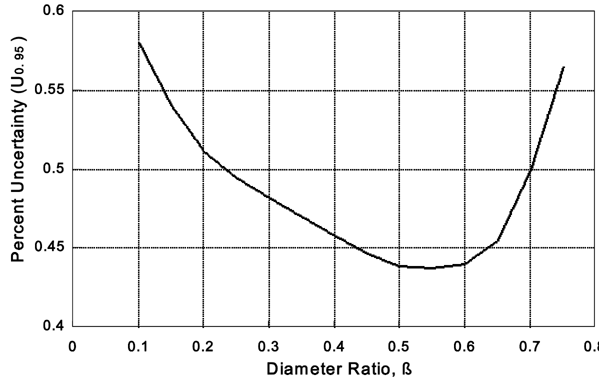

FIGURE 3: UNCERTAINTY OF EMPIRICAL DISCHARGE COEFFICIENT AT INFINITE REYNONDS NUMBER

CONCLUSION

In general, factors associated with orifice installation affect the overall errors in flow measurement. Errors are due to uncertainties in, (a) flow equation, (b) actual physical properties of the flowing fluid, and (c) dimensions of the flow meter.

The most important assumption for the orifice discharge coefficient equation is that the systematic biases of equipment are randomized in the data base. This allows the use of empirical coefficient of discharge on dynamically similar flow meter without requiring the measurement equipment be identical. For the discharge coefficient either the empirical equation or actual flow calibration may be used to ascertain the error.

The flow rate is calculated from a number of variables, the discharge coefficient, expansion factor, differential pressure, bore diameter, pipe diameter, and the fluid density and viscosity, which are derived from temperature and pressure values of the flowing fluid. Therefore, actual fluid properties should be monitored with best possible precision.

The mechanical tolerances are critical for measurement accuracy. The seat gap, sealing material and dimensions, recesses and protrusion, plate flatness and eccentricity, tap location and machining tolerances, etc., must conform to the standard to achieve flow rate measurement within the stated uncertainty of the standard.

Assuming that the flow meter installation, mechanical tolerances conforms with the standard and all measured parameters are monitored with precautions to minimize measurement error, the estimated measurement uncertainty for an orifice flow meter is shown in Figure 4.

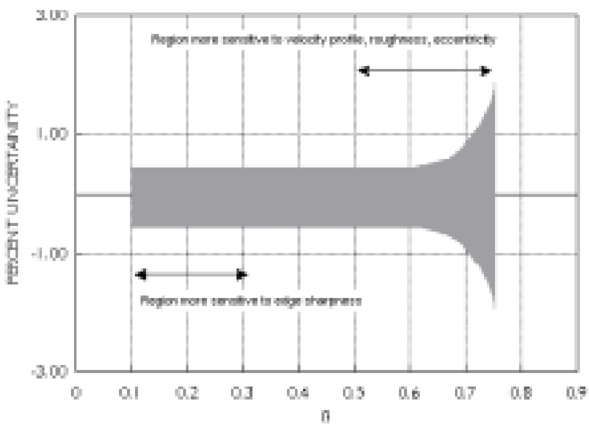

FIGURE 4: PRACTICAL UNCERTAINTY LEVELS

Orifice plates whose bore diameters are less than 0.45 inches may have coefficient of discharge uncertainties as great as 3.0% because of problems with edge sharpness. The uncertainty band shown in Figure 4 also assumes that the plate inlet velocity profile is fully developed and has undisturbed flow pattern.

An error band for an orifice meter is usually estimated from the uncertainty assigned to the differential pressure monitoring device and that value depends on the performance specification of the differential pressure device.

In general, most of the restrictions imposed by the standards are based on the tolerances of the equipment and instruments used for the tests generating the data base. Some were defined by well controlled laboratory tests. When any tolerance limit of the standard is exceeded, the stated uncertainty of the standard may not be applicable and may result in additional measurement uncertainty. However, in some cases experimental data base is not available to predict this additional uncertainty.

An orifice flow meter that conforms to the mechanical tolerances and installation specifications stated in the Standard, has properly selected, maintained, and calibrated instruments or secondary devices, should have a system uncertainty of better than ±1%. Deviations from the standard practices and allowable limits could result in erroneous measurement. Effects of some deviations of mechanical tolerances have been experimentally investigated and results can predict the error with reasonable accuracy. To avoid any controversy and limit the measurement uncertainty, it is better to be careful and install orifice meters in accordance with the Standards.

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